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***published in***

Journal of Strength and Conditioning Research  
2020

***DOI (link to publisher)***

[10.1519/JSC.0000000000002765](https://doi.org/10.1519/JSC.0000000000002765)

***document version***

Publisher's PDF, also known as Version of record

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***citation for published version (APA)***

Huurnink, A., Fransz, D. P., de Boode, V. A., Kingma, I., & van Dieën, J. H. (2020). Age-Matched Z-Scores for Longitudinal Monitoring of Center of Pressure Speed in Single-Leg Stance Performance in Elite Male Youth Soccer Players. *Journal of Strength and Conditioning Research*, 34(2), 495-505.  
<https://doi.org/10.1519/JSC.0000000000002765>

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# AGE-MATCHED Z-SCORES FOR LONGITUDINAL MONITORING OF CENTER OF PRESSURE SPEED IN SINGLE-LEG STANCE PERFORMANCE IN ELITE MALE YOUTH SOCCER PLAYERS

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<sup>1</sup>Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, the Netherlands; <sup>2</sup>Department of Radiology and Nuclear Medicine, Academic Medical Center, University of Amsterdam, Amsterdam, the Netherlands; <sup>3</sup>Department of Orthopaedic Surgery, Maastricht University Medical Center, Maastricht, the Netherlands; and <sup>4</sup>Adidas MiCoach Performance Centre, AFC Ajax, Amsterdam, the Netherlands

## ABSTRACT

Huurnink, A, Fransz, DP, de Boode, VA, Kingma, I, and van Dieën, JH. Age-matched z-scores for longitudinal monitoring of center of pressure speed in single-leg stance performance in elite male youth soccer players. *J Strength Cond Res XX(X)*: 000–000, 2018—Coordination of corrective motor actions is considered important for soccer performance and injury prevention. A single-leg stance (SLS) test assesses the integrity and proficiency of the sensorimotor control system, quantified by center of pressure averaged speed (COPspeed). We aimed to provide age-matched z-scores for COPspeed in elite male youth soccer players. Second, we assessed a threshold for abnormal long-term change in performance, i.e., critical difference (CD). In a youth academy program, 133 soccer players of 9–18 years were tested twice for both legs (2 repetitions), and one repetition follow-up was conducted at 5.8 months (SD 2.7). Linear regression between age and COPspeed was performed to provide age-matched z-scores. Variance of differences in z-scores at baseline and between sessions was used to estimate the CD up to 5 repetitions. Intraclass correlation coefficients (ICCs) were assessed within and between sessions. The age significantly affected COPspeed ( $p < 0.0001$ ), with lower values in older players (95% confidence interval; 3.45–9.17 to 2.88–5.13  $\text{cm} \cdot \text{s}^{-1}$ , for 9 and 18 years, respectively). The z-score CD ranged from 1.72 (one repetition) to 1.34 (5 repetitions). The ICC of z-scores was 0.88 within session and 0.81 between sessions. In conclusion, the SLS performance in elite male youth soccer players improves with age. We determined age-matched z-scores of COPspeed, which reliably

determined performance according to age. The CD allows for detection of abnormal variations in COPspeed to identify players with a (temporary) deterioration of sensorimotor function. This could be applied to concussion management, or to detect underlying physical impairments.

**KEY WORDS** one-leg stance, minimal detectable difference, critical difference, reliability, sensorimotor control

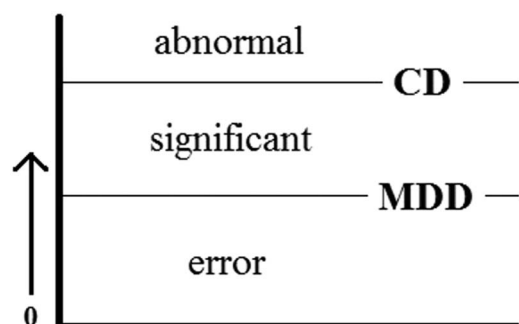
## INTRODUCTION

In soccer, various laboratory and field tests have been applied to characterize potential determinants of performance and include general motor abilities (e.g., aerobic and anaerobic capacity, flexibility, speed, agility, and strength), sport-specific technical skills (e.g., dribbling and passing), and sport-specific perceptual-cognitive skills (e.g., decision-making and pattern recognition) (19,28,37,42,62). Potentially, a test battery could be helpful within a multidimensional approach to identify talent at an early age, evaluate functional progress, assess injury risk, or identify suboptimal physical functioning (19,47). The latter could be important to guide individual training regimes.

Recently, it was suggested that assessment of single-leg stance (SLS) tests should be included in monitoring of elite soccer players and that this monitoring would be most valuable during the development of youth players (47). The SLS is assumed to provide information about the total body sensorimotor control system, which consists of the detection of sensory information, integration in the central nervous system, and release and execution of motor commands (64). The sensorimotor control during standing on one leg depends on feedback (54) to accurately coordinate the timing and magnitude of corrective motor actions (58). In soccer, this coordination of corrective motor actions is

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*Journal of Strength and Conditioning Research*  
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**Figure 1.** Y-axis represents the absolute difference between the 2 measurement outcomes. A difference below the MDD can be considered as an error relative to a similar true score. A difference between the MDD and CD can be considered significant, with a real change in true score. A difference above the CD can be considered abnormal over time. CD = critical difference; MDD = minimal detectable difference.

considered important, for instance, to control the body during demanding, rapidly changing, or unexpected movement (58), to protect joint ligaments (21,45,64), and to avoid traumatic injury (59). In contrast to the highly dynamic motor behavior during soccer, the purpose of the SLS is to stand as motionless as possible. Given the fact that no predefined motor actions or perturbations are involved, the task is very standardized, and aims to specifically test the integrity and proficiency of the sensorimotor control system. Therefore, SLS performance can be considered a basic attribute of a player within the category of general motor ability.

The SLS performance can be quantified by force plate recordings. Commonly, center of pressure (COP) trajectory parameters are used, such as the averaged distance to the COP origin, a 95% COP area, the averaged COP speed, or various nonlinear measures (25,26,36,40,47,51,64). In general, these COP parameters provide very similar information (8,11,12,51). This is important because the application of more outcome measures will reduce the power or increase the like-

lihood of type I errors. Hence, when possible, it is preferable to select as few outcome measures as possible. Although all COP parameters are considered sufficiently reliable, the averaged COP speed (COPspeed; total COP path length divided by time) was consistently among the most reliable ones (8,14,16,50,51). Moreover, COPspeed was more responsive to training (24,36) and was more sensitive to differences between groups (9,23,31,32,50,51,57,63) than other COP parameters. These findings indicate that the application of COPspeed only should suffice to quantify SLS performance.

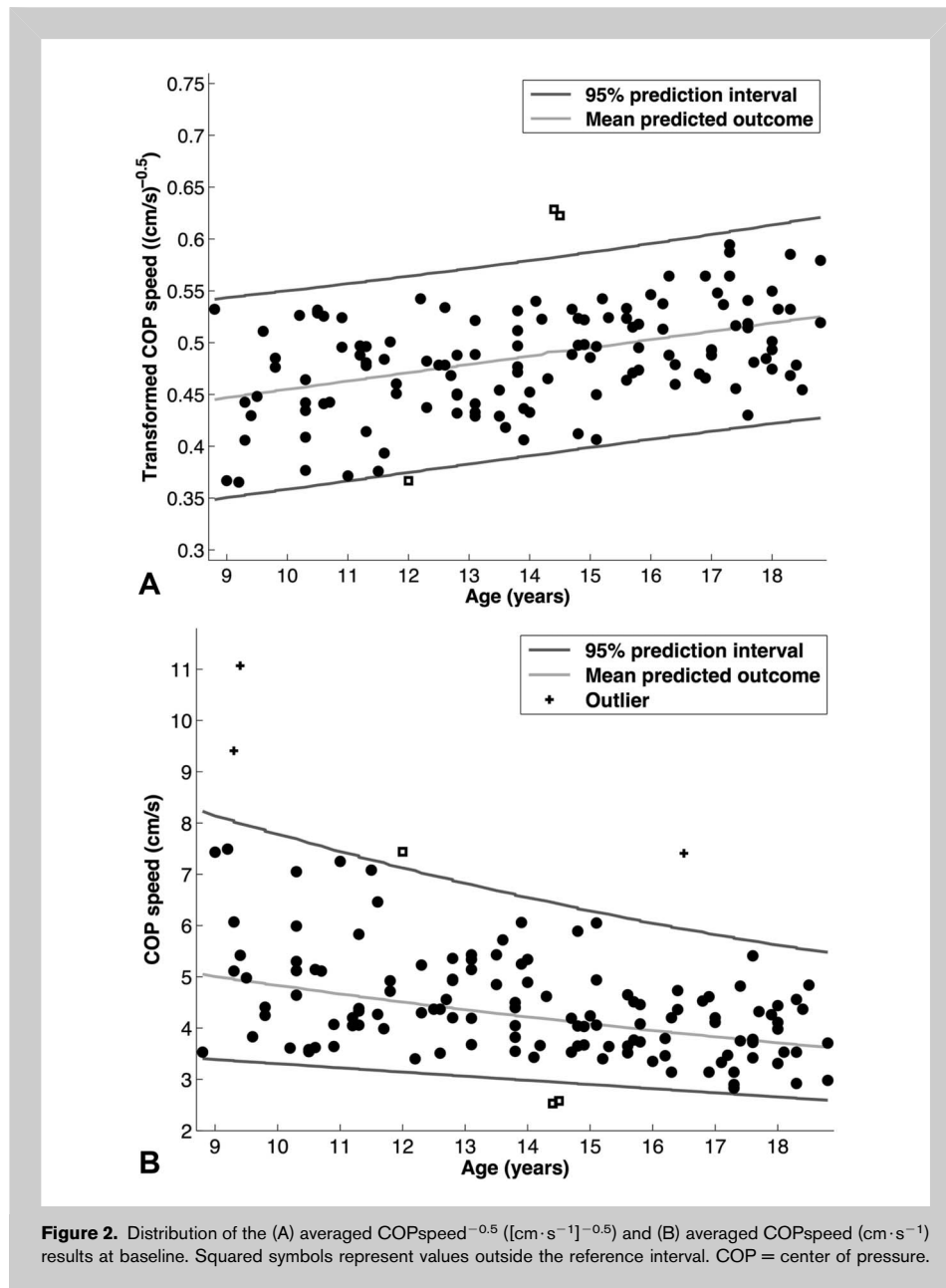
Given that COPspeed reflects the faster COP movements that correct displacements of the center of mass of the body (17), COPspeed reflects a combination of body sway and the extent of corrective motor actions. With the aim to stand as motionless as possible, in general, a lower COPspeed can be considered a better SLS performance. In support of this, it was shown that 12 weeks of recreational soccer training in untrained men resulted in a larger decrease of COPspeed than 12 weeks of recreational running and no training (24). Furthermore, for soccer players, a lower COPspeed during SLS was associated with a higher level of competition (25,55). This was also found in a comparison of lower and higher professional level soccer players with similar training intensity (55). Conversely, fatigue due to repeated sprints induced an increase in COPspeed in young soccer players (47). The same was true after various injuries, such as ankle sprains (18), anterior cruciate ligament (ACL) ruptures (40), and concussions (49). This wide range of conditions reflects the responsiveness of the SLS and COPspeed to changes or to suboptimal functioning of parts of the control system. Moreover, COPspeed was a significant predictor of ankle sprains (64). This strengthens the general concept that SLS performance (COPspeed) reflects the ability to coordinate corrective motor actions, which are presumed important to reduce injury risk of, for instance, ankle sprains (21).

To date, guidance on how to use and interpret SLS performance in sports is lacking, especially with regard to the individual level. For successful incorporation of SLS in regular monitoring of youth soccer players, specific reference

**TABLE 1.** Player's characteristics.\*

Age	<i>n</i>	Body mass (kg)	Length (cm)	Time between sessions (mo)	Preferred kicking leg (% right)
9–10	26	35.7 (5.4)	1.45 (0.07)	7.9 (1.5)	77%
11–12	24	45.9 (9.8)	1.59 (0.12)	7.2 (3.6)	71%
13–14	30	59.4 (9.0)	1.71 (0.08)	5.8 (2.0)	70%
15–16	25	71.3 (8.6)	1.77 (0.08)	4.7 (1.5)	84%
17–18	28	75.5 (7.6)	1.81 (0.07)	3.7 (2.0)	71%
Total	133	58.0 (17.0)	1.67 (0.16)	5.8 (2.7)	75%

\*Values presented as mean (*SD*).



values are needed. In general, to identify players with abnormally low or high performance, a population-based reference interval may be applied, which is based on a single measurement outcome for each individual (7,13,39). A 95% interval of the results of a reference population can be deemed normal (i.e., the reference interval) (61). In addition, the detection of abnormal functioning may be improved by considering the baseline value of a player (13). However, to do so, it is essential to estimate precision of measurements, systematic changes, and normal long-term variations in performance in the specific population of interest. The precision of measurement can be determined by the variation of performance during

of COPspeed, (b) to assess within-session and between-session reliability, and (c) to determine MDD and CD for personal development.

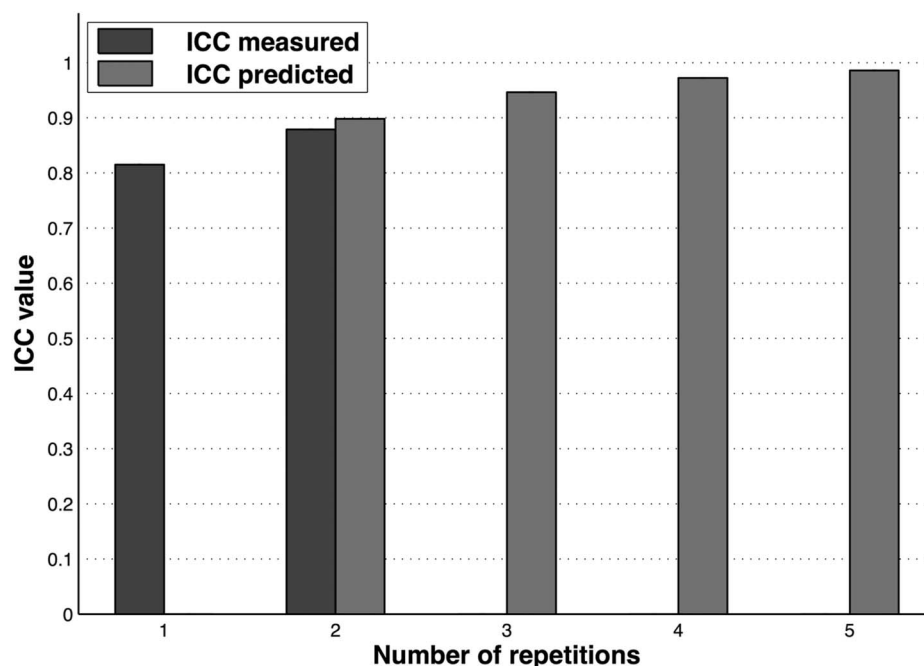
## METHODS

### Experimental Approach to the Problem

The youth academy of AFC Ajax performed regular monitoring of SLS performance on a force plate, whereby all players were measured at least twice in a season. From this database, we retrieved the first 2 measurement sessions of all youth players available, as well as player characteristics such as age, body mass, body length, and preferred leg to take a penalty at the time of the measurements. The

a single test session, with the assumption that this variation in performance is irrelevant. Hence, it quantifies the minimal detectable difference (MDD). A change in performance above the MDD value can be considered significant. However, due to systematic change and normal long-term variation in performance, a significant change in performance of a player can still be within the reference interval. Therefore, variation in performance between sessions over a longer time can be used to assess abnormal change in performance, which we denote as the critical difference (CD) (Figure 1) (13).

To the best of our knowledge, reference values and long-term fluctuations in SLS performance have not been established for elite male soccer players aged from 9 to 18 years. Among elite soccer players, it was shown that young adolescents had higher COPspeed values compared with adults (48). Furthermore, previous studies suggested that, among children, differences in SLS performance are present between age groups (6,29). Therefore, we hypothesize that the COPspeed is lower in older players. The aims of this study were (a) to assess age-dependent reference values of SLS performance in male elite youth soccer players by means



**Figure 3.** Within-session reliability of z-score with different number of repetitions. ICC measured: single (1 repetition with both legs) and average (2 repetitions with both legs) value. ICC predicted: ICC Spearman-Brown =  $n$  (number of trials)  $\times$   $ICC_{\text{single}} / (1 + (n - 1) \times ICC_{\text{single}})$ . ICC = intraclass correlation.

COPspeed for each trial was calculated. The purpose of the SLS task was to stand as motionless as possible; hence, a higher COPspeed value reflects a worse SLS performance. Regression analyses were applied to calculate age-matched z-scores of the average outcome value per player for session 1. Within-session and between-session reliability was assessed using intraclass correlation coefficients (ICCs). Variability of outcomes within session 1 was used to estimate the MDD for 1 to 5 repetitions (for both legs). Variability between sessions was used to estimate the long-term CD for 1 to 5 repetitions as a reference of abnormal change over time.

### Subjects

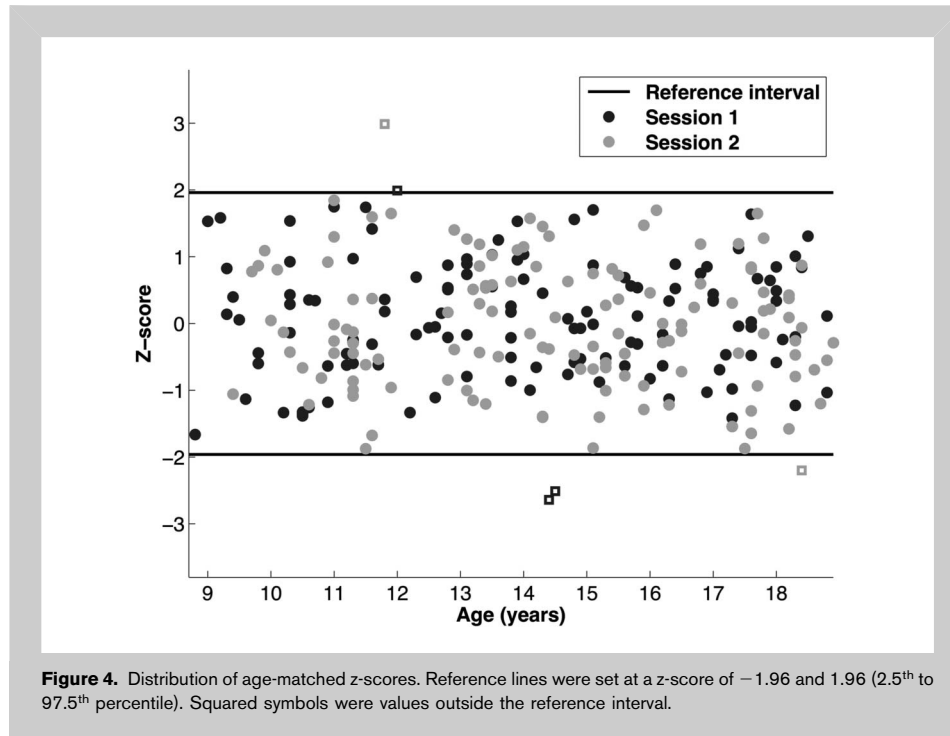
The participants of this study were 133 elite male youth soccer players (9–18 years), who attended the youth academy of AFC Ajax (Table 1). At the time of measurements, all participants were fit to perform at the highest standard of competitive soccer matches for their age group. Written parental consent and participant consent were collected and ethical approval was granted by the ethical review board of the Faculty of Human Movement Sciences of the VU (ECB 2014–80) in accordance with the Declaration of Helsinki.

### Procedures

Measurements were performed in a testing facility at the AFC AJAX youth academy. For each participant, 2 consecutive test sessions were analyzed. The initial

session consisted of 2 trials of SLS per leg, whereas the follow-up session consisted of one trial per leg. Legs were tested in alternating order, with the left leg being tested first. All participants completed the regular warming-up routine (about 15 minutes), which consisted of jogging 2 laps around the pitch, followed by dynamical stretch exercises, and subsequently,  $5 \times 50$  m runs at approximately 80% of maximum pace. For measurements, players were asked to stand as motionless as possible on one leg on a force plate for 30 seconds (s), with eyes open, hands on the hips, and looking at a black cross ( $30 \times 30$  cm) positioned on a blank wall 4 m away (27,47,55). Employment of 20–30-second stance duration has shown to provide reliable COPspeed results, with high ICC values within a test session ( $ICC > 0.90$ ) (23) and between test sessions ( $ICC > 0.80$ ) (38). If a participant touched the floor with the other leg, or if arm movement was used to regain balance, the trial was discarded and repeated. All trials were performed without shoes. One practice trial per leg was performed before actual testing commenced. The player's leg of preference to take a penalty kick was considered as the "kicking leg" and the other leg was denoted as the "stance leg."

**Data Processing.** Ground reaction forces (GRF) were recorded at 1,000 samples/s, using a  $40 \times 60$  cm AMTI force plate (type BP400600HF; Advanced Medical Technologies, Inc.,



Watertown, MA, USA), which was mounted flush with the floor. A custom MATLAB (The Mathworks, Natick, RI, USA) program was designed for data reduction. The GRF data were filtered with a bidirectional low-pass Butterworth filter with a cutoff frequency of 20 Hz (22). The COP was calculated in accordance with the manufacturer's manual. The resultant COPspeed was calculated by dividing the total COP path length (cm) by trial duration (30 seconds).

#### Statistical Analyses

Statistical analyses were performed with SPSS (version 22.0; SPSS, Inc., Chicago, IL, USA). To test the effect of age, the outcomes at baseline (session 1) were averaged. The Dixon's range statistic revealed 3 outliers, which were removed from further analyses because these would substantially alter the distribution (Figure 2). Because COPspeed was not normally distributed (skewness 1.04; kurtosis 1.23; Shapiro-Wilk's W test  $p < 0.001$ ), it was transformed by means of the power of  $-0.5$  ( $\text{COPspeed}^{-0.5}$ ) (skewness  $-0.04$ ; kurtosis 0.13; Shapiro-Wilk's W test  $p = 0.40$ ) (5). Linear regression between the averaged  $\text{COPspeed}^{-0.5}$  per player and age was performed to obtain the age-dependent mean value. The averaged  $\text{COPspeed}^{-0.5}$  per player was used to calculate the z-scores:  $-(\text{COPspeed}^{-0.5} - \text{age-dependent mean COPspeed}^{-0.5}) / \text{SD of COPspeed}^{-0.5}$ . Subsequently, the outcomes of all trials (3 repetitions  $\times$  2 legs) were expressed in age-matched z-scores. The z-score is a standardized scoring tool to indicate how many SDs an observation is above or below the mean of the reference population. As a consequence, the z-scores are corrected for age and non-

normality. The age-matched z-scores were considered for further analyses.

A repeated-measures analysis of variance (ANOVA) design was used to test the effect of leg (kicking leg vs. stance leg), repetition (3 repetitions), and their interaction. Statistical significance was set at  $p < 0.05$  for Wilks lambda. If necessary, for post hoc comparisons, Sidak's correction for multiple testing was applied. Within-session reliability was assessed by means of the ICC based on the 4 trials (2 repetitions) of session 1 (2-way random model, absolute agreement). To express the effect of the number of repetitions, Spearman-Brown ICC values were calculated for 1 to 5 repetitions:  $\text{ICC}_{S-B} = n$  (num-

ber of trials)  $\times \text{ICC}_{\text{single}} / (1 + (n - 1) \times \text{ICC}_{\text{single}})$  (10). The long-term between-session reliability was assessed by means of  $\text{ICC}_{\text{single}}$  and  $\text{ICC}_{\text{average}}$  based on the averaged outcomes of sessions 1 and 2.

With regard to the potential to follow personal development, the SEM, MDD, and long-term CD were assessed for the average value of both legs (i.e., 1 repetition). Based on the assumption that the contribution of "error" to the "true" score was similar across repetitions (10), the following equations were used to estimate MDD and CD for 1 to 5 repetitions within a session:

$$\text{SEM} = \frac{\sigma_1}{\sqrt{2}},$$

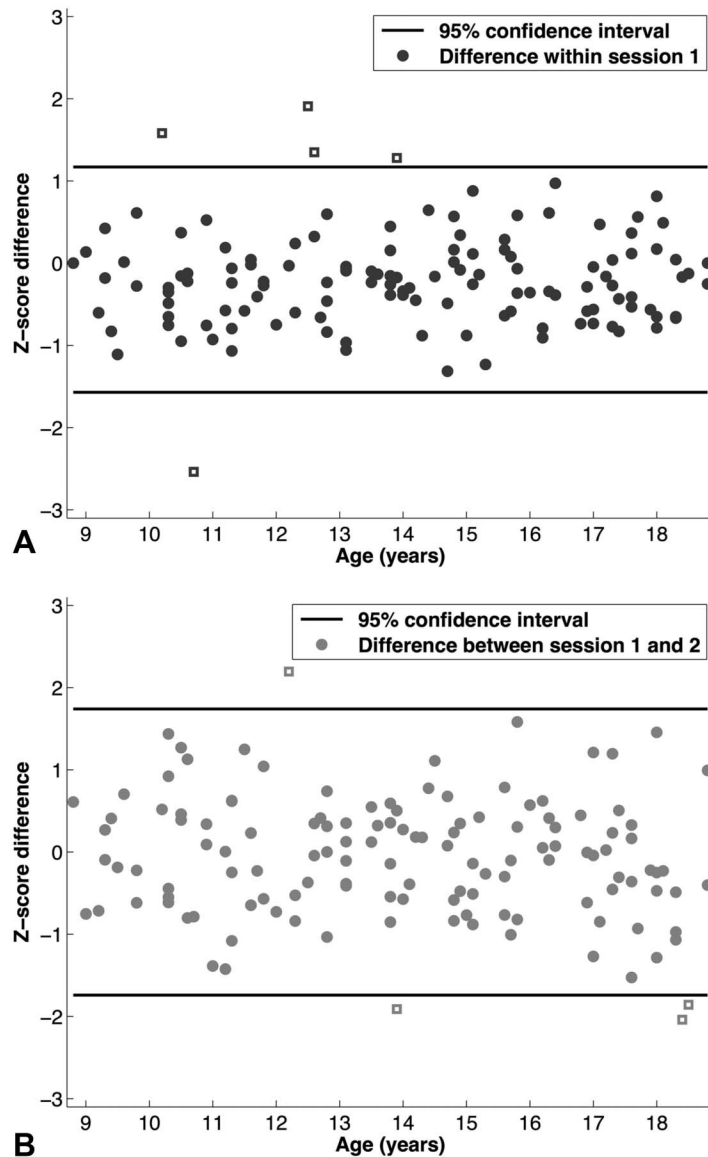
SEM: standard error of measurement and  $\sigma_1$ : variance (SD of difference) between repetitions 1 and 2 of session 1.

$$\text{MDD} = \frac{1.96 \times \text{SEM} \times \sqrt{2}}{\sqrt{n}},$$

MDD: minimal detectable difference of 2 consecutive measurements;  $\sqrt{2}$ : represents the 2 measurements; and  $\sqrt{n}$ : represents the number of repetitions used to calculate the outcome values.

$$\sigma_e = \sqrt{\left(\frac{\text{SEM}}{\sqrt{n1}}\right)^2 + \left(\frac{\text{SEM}}{\sqrt{n2}}\right)^2},$$

$\sigma_e$ : expected variance between 2 measurements, when only "error" (i.e., SEM) accounts for variability and  $n1$  and  $n2$ :



**Figure 5.** A) Differences between repetition 1 and 2 within session 1. Lines represent the corresponding calculated minimal detectable difference, corrected for the systematic change. B) Differences between session 1 and 2. Lines represent the corresponding calculated critical difference.

number of repetitions for both outcome values. We make the explicit assumption that within-session variation in performance is irrelevant biological variation.

$$\sigma_e = \sqrt{\left(\frac{SEM}{\sqrt{2}}\right)^2 + \left(\frac{SEM}{\sqrt{1}}\right)^2},$$

$\sigma_e$ : expected variance between the 2 sessions due to “error” (2 repetitions for session 1 and 1 repetition for session 2).

$$\sigma_t = \sqrt{\sigma_m^2 - \sigma_e^2},$$

$\sigma_t$ : estimated variance between the present 2 sessions only due to variance in “true” score (fixed value); and  $\sigma_m$ : actually measured variance between the 2 sessions.

$$CD = 1.96 \times \sqrt{\sigma_e^2 + \sigma_t^2},$$

CD: critical difference between 2 outcome values;  $\sigma_t$ : estimated variance between sessions due to variance in “true” score (see 5); and  $\sigma_e$ : estimated variance between sessions due to variance in “error” (dependent on the number of repetitions; see 3).

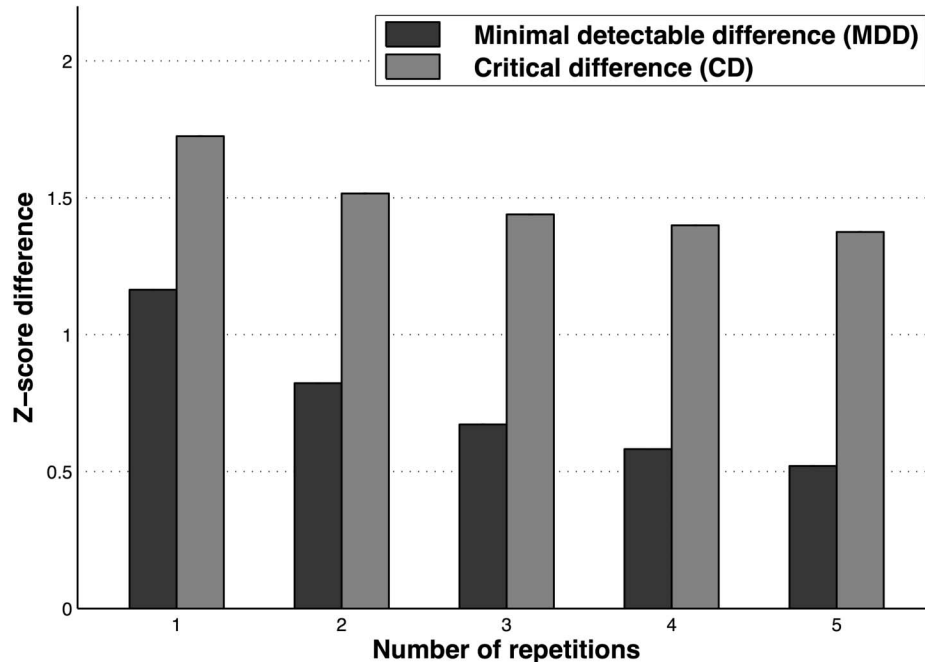
## RESULTS

### Age Effect

After transformation of the COP-speed values of session 1, regression analyses between age and the averaged transformed data ( $\text{COPspeed}^{-0.5}$ ) revealed a significant association ( $p < 0.0001$ ;  $R^2$  0.18) (Figure 2A). For a more intuitive interpretation, the 95% prediction interval and the data were transformed again to COP-speed, which clearly illustrates a lower speed and lower between-subject variance for older players (Figure 2B). The age-dependent mean of  $\text{COPspeed}^{-0.5}$  ( $[\text{cm} \cdot \text{s}^{-1}]^{-0.5}$ ) was  $0.383 + 0.008 \times \text{age (year)}$  (Figure 2A). The  $SD$  of  $\text{COPspeed}^{-0.5}$  was  $0.0518 \text{ cm} \cdot \text{s}^{-1}$ . Therefore, the age-matched z-score (Figure 3) can be calculated as follows:

$$\text{z-score} = -\left(\left(\text{COPspeed}^{-0.5} [\text{cm} \cdot \text{s}^{-1}] - (0.383 + 0.008 \times \text{age}[\text{year}])\right) / 0.0518\right).$$

The minus sign was included to correct for the transformation effect (COPspeed values higher than the mean are transformed into  $\text{COPspeed}^{-0.5}$  values lower than the mean).



**Figure 6.** Estimated effect of number of repetitions (up to 5) on the minimal detectable difference and long-term critical difference of z-scores.

and vice versa (Figure 2)). The resultant z-scores thus indicate better performance for lower scores.

#### Repetition and Leg Effect

The repeated-measures ANOVA showed a significant effect of repetition ( $p = 0.002$ ), with a higher z-score in repetition 1 compared with repetition 2 [mean difference: 0.19 (95 [confidence interval] CI 0.06–0.31)]. Session 2 (repetition 3) was similar to session 1 (repetition 1 [ $p = 0.12$ ] and repetition 2 [ $p = 0.94$ ]). The z-scores of the kicking leg and stance leg were similar ( $p = 0.16$ ; mean difference: 0.09 [95 CI –0.04 to 0.21] higher for the stance leg). There was no statistically significant interaction between repetition and leg ( $p = 0.65$ ).

#### Reliability of Z-Score

The 4 trials in session 1 (i.e., 2 repetitions for both legs) resulted in an ICC value of 0.88 (95 CI 0.84–0.91). Separated for kicking leg and stance leg, ICCs for 2 trials were 0.87 (95 CI 0.81–0.91) and 0.84 (95 CI 0.77–0.89), respectively. The ICCs for 1 to 5 repetitions based on the Spearman-Brown prediction formula are illustrated in Figure 3. For the between-session reliability (average time span of 5.8 months [ $SD$  2.7]), the z-scores were averaged for each session. The ICC<sub>single</sub> (1 session) was 0.68 and the ICC<sub>average</sub> (2 sessions) was 0.81 (95 CI 0.73–0.87).

#### Standardized Reference

The population reference interval of the mean z-scores was set at –1.96 to 1.96, which is concordant with a 95% pre-

diction interval. Session 1 showed 0.8% of the players to have z-scores above (outliers included: 3.0%) and 1.5% of the players to have z-scores below the reference interval (Figure 4). Even with 1 repetition, compared with 2 repetitions in session 1, the distribution of z-scores of session 2 was very similar to session 1, with 0.8% of the players above (outliers included: 3.0%) and 0.8% of the players below the reference interval.

The *SEM* of the z-score for 1 repetition (averaged for both legs) was 0.42. The distribution of the differences in age-matched z-scores within and between sessions was similar over age (Figure 5). This indicates that the MDD and CD apply to all age groups. The estimated MDD ranged from 1.16 for 1 repetition to 0.52 for 5 repetitions per session (Figure 6). The estimated CD ranged from 1.72 for 1 repetition to 1.38 for 5 repetitions per session (Figure 6).

#### DISCUSSION

This study evaluated the performance on the SLS test by means of COPspeed over 30-second trials in elite male soccer players of 9–18 years. The main finding was that COPspeed was significantly associated with age, with lower values and lower variance for older players. Therefore, care should be taken to compare or pool COPspeed among different age groups. Instead, the current age-matched z-scores may be reliably used, with high within-session reliability and acceptable between-session reliability. To detect abnormal SLS performance, a population reference limit of –1.96 to



1.96 (2.5<sup>th</sup> to 97.5<sup>th</sup> percentile) can be applied. However, if a baseline value of a player is known, the detection of abnormal function can be further improved by the application of the CD. Although depending on the number of repetitions, a change in performance larger than 1.5 (z-score) can be considered as abnormal for 2 repetitions.

The significant association between age and COPspeed during SLS is in line with previous research concerning bipedal stance (1,3,41). Furthermore, Condon et al. (6) showed that older age groups of children were able to sustain a SLS for a longer period. Presumably, this increase in performance over age is mainly due to sensorimotor development (2,3,33,43,44,65). Another explanation that has been put forward is a lack of concentration in younger players, possibly due to boredom or a lower attention capacity (29,43). In the present sample, only a selected group of players made it through the entire youth academy program. Therefore, the lower COPspeed and variance in older players might in part be determined by selection bias. In addition, maturation is an important factor to consider (53,59); more mature players have altered body composition and higher muscle strength, but it is unclear how this would affect COPspeed. Nevertheless, given that the present upper reference (z-score 1.96) for players of 9 years ( $9.17 \text{ cm} \cdot \text{s}^{-1}$ ) would correspond to a z-score of around 12 for the players of 18 years, there is an obvious need to correct COPspeed values for age.

The within-session reliability of age-matched z-scores was high (ICC 0.88) for 2 repetitions with both legs, which is comparable with the often applied tests of speed and agility, but considerably higher than tests for technical skills and time to stabilization after hop landings in a comparable sample of elite male youth soccer players (20,52). In the absence of a significant difference between one leg and the other, one may opt to pool the outcome values of both legs in line with Höner et al. (2015). This will improve precision of measurement (Figure 3) and likely increase the construct validity to assess total body sensorimotor function. However, asymmetrical impairments in SLS performance have previously been described after injuries such as ACL ruptures (40).

The between-session reliability (with, on average, 6-month period between sessions) of z-scores was within the acceptable range (ICC<sub>single</sub> 0.68; ICC<sub>average</sub> 0.81) for diagnostic use. This could lead to the potential to assess deviant levels of performance and to include SLS performance in prognostic studies (19,20). Again, between-session reliability was comparable with running speed and agility (20). It should be noted that our session 2 only consisted of 1 repetition, to minimize the burden for players and coaches. Between-session reliability will improve if 2 or 3 repetitions are measured (Figures 3 and 6). Only a small systematic decrease of z-scores was observed over the 2 repetitions within session 1. This indicates a fast learning effect, which is likely to extinguish over a number of repetitions (12). Until

now, it is unknown what the effect of long-term repetitive testing is on the COPspeed values. The presented z-scores did not demonstrate a systematic effect over 3 to 12 months.

The z-scores can be used to identify players with unusually low or high SLS performance by means of the reference interval (61), but the z-scores can also be applied in a probabilistic way (19,35). For instance, in recreational basketball players, a “dose response” relation has been shown between SLS performance groups (i.e., low sway: z-score  $<-0.5$ ; mid sway: z-score  $-0.5$  to  $0.5$ ; and high sway: z-score  $>0.5$ ) and the risk of a first-time ankle sprain incidence. The 70 players in the “high sway” group had a more than 5 times increased risk compared with the 70 players in the “low sway” group (35). In general, a low SLS performance suggests a low total body sensorimotor control, which could be a concern for the athlete. Impairments may lead to a higher susceptibility to injuries and less effective physical training (4,15,45). The z-scores of SLS performance can possibly be used, in combination with other tests, to guide talent selection, return-to-play decisions, or target the load and focus of individual training regimes.

The detection of abnormal SLS performance may be improved when baseline values of an athlete are taken into account (13). This assumption is strengthened by the determined CD of 1.5 in z-score. For instance, a player with an initial z-score of  $-1$  may over time develop a z-score of  $0.6$ . This value is well within the population reference interval of  $-1.96$  to  $1.96$ , indicating normal SLS performance when compared with the reference data. However, the decline by 1.6 points exceeds the CD (1.5 for 2 repetitions), hence indicating abnormal change of performance. To date, it is unknown when a decline in SLS performance should raise concerns about the state of an athlete. An increase in z-score above the CD should be considered as an abnormal change in total body sensorimotor control, warranting additional evaluation of possible causes.

One way to estimate the effectiveness of the SLS performance test to identify individuals with impaired sensorimotor control is to compare the present reference interval and CD with the results of previous studies (18,40,49,64). However, these studies differ considerably in population sample (age, sport type, and sport level) and experimental setup (distance to visual target and data reduction) compared with this study, which has a strong detrimental effect on the comparisons (25,30). Huurnink et al. (2013) reported COPspeed values of field hockey players (mean age of 19 years, high level of competition), whereby all impaired players were above the reference interval, and the other players were mostly within the reference interval. By contrast, Holme et al. (1999) reported mean COPspeed values of  $1.96$ – $2.37 \text{ cm} \cdot \text{s}^{-1}$  for recreational adult athletes 6 weeks after an ankle sprain, which are all well below our reference interval. However, important factors that could reduce COP movement, such as the distance to a visual target and filtering of the force signal, were not reported.

As a consequence, these lower COPspeed values remain unexplained. Therefore, it may be better to compare the effect sizes of previous studies with the current reference intervals. Because the Cohen's  $d$  (mean difference/ $SD$ ) is normalized to the  $SD$  of the results, these effect sizes are directly comparable with the current z-scores (mean/ $SD$ ). In previous studies, Cohen's  $d$  ranged from 0.7 to 1.4 for ACL rupture without reconstruction (40), previous lateral ankle ligament rupture (23), concussion (49), and fatigue induced by a repeated-sprint protocol (47). It is likely that these averaged effect sizes underestimate the true effect on the individual impaired player, as for instance, not all concussions will lead to a diminished sensorimotor control. Despite this, the effect sizes indicate that it is possible that the present population reference interval (z-scores  $-1.96$  to  $1.96$ ) would be insufficient to detect these relevant impairments in individual players. Because, as indicated above, it is also possible to apply the z-scores in a probabilistic way, future studies could be directed to categorizing players in performance groups based on the z-scores (35). For detecting impairments in sensorimotor control that occur after baseline measurements, the Cohen's  $d$  values indicate that the MDD/CD of 3 repetitions (0.67 and 1.43, respectively) would probably suffice to detect most of the impaired players.

The MDD value quantifies the precision of measurement, with the assumption that biological variation within a measurement session can be considered as irrelevant. Therefore, a change in performance below the MDD should not be considered meaningful. Furthermore, the MDD can be used to signify outliers during testing. This would allow to repeat these trials. Although within-session reliability was deemed high, the presented MDD values (1–5 repetitions: 0.52–1.16) indicate that the measurement error is substantial within a single player. Therefore, when changes in SLS performance within a short-time interval are of interest, for instance, during the rehabilitation of a concussion or to assess the effect of fatigue, it seems preferable to use more repetitions. Note that conducting more than 5 repetitions per leg is uncommon. Although not fully investigated, fatigue or (reduction of) concentration might ameliorate any benefit to precision of measurement.

Several limitations need to be addressed. The present reference values are likely to be affected by the used measurement setup. Especially, a structured visual target placed at a shorter distance (currently at 4 meters) will reduce task difficulty (30). This will result in lower COPspeed values and might decrease the sensitivity of the test (30). The excluded 3 outliers may have been part of the normal distribution; however, we believe that it was more important to protect the distribution from very high non-normality than to censor the data points above the reference interval. In addition, we did not consider history of injuries before testing or between measurement sessions; hence, we cannot rule out that historical serious injuries

may have influenced the results of some players (9,23,40). Given that we did not exclude individuals based on previous injuries and the relatively large sample size, the present results seem representative for male elite youth soccer players who are fit to perform at the highest standard of competition. Furthermore, we did not provide the status of maturation, which may well be a mediator to impaired functional performance or injury risk, especially in the group of 13–16 years (59). It has been postulated that during the period of rapid growth, the coordinative skill is temporarily decreased (59). However, we did not measure an increase in variance, nor a systematic increase of COPspeed in players from 13 to 16 years compared with the younger and older players (Figure 2B). The age-matched z-scores can be used to assess the independent effect of maturation on sensorimotor control.

The age groups had a different mean follow-up period (Table 1). Therefore, we calculated a post hoc Pearson correlation coefficient between period of follow-up and COPspeed differences between sessions 1 and 2, for 9–12 years and 13–18 years. Given the correlation coefficients were very low ( $-0.04$  &  $-0.06$ , respectively), we think it is unlikely that time differences in follow-up significantly affected our results. Furthermore, the current number of repetitions of SLS was relatively low. This was chosen to minimize the burden for players and coaches in view of the regular monitoring. Therefore, the effect on ICC, MDD, and CD of more repetitions are estimations based on the assumption that the contribution of “error” to the “true” score was similar for the repetitions (10).

It has been postulated that there exist sport-specific alterations in postural control (25). Therefore, an SLS test during a ball kick movement of the contralateral leg, as reported by Teixeira et al. (2011) (60), may improve ecological validity. In addition, various other balance tests exist, for instance, to re-weight relevance of sensory modalities (eyes closed), increase difficulty (unstable surface, jump landing, Star Excursion Balance Test [SEBT]), and to improve the practical applicability as well (SEBT) (34,52,56,60). All these modes of SLS introduce extra sources of variance and target, to some extent, other aspects of the neuromusculoskeletal functioning (46,56). Therefore, generalizing the present results to other balance tasks should be conducted with some degree of caution. This is especially true for the SEBT, which was previously shown to be unrelated to COPspeed in different modes of SLS (56). It was postulated the SEBT was more dependent on muscle strength and flexibility, which, in view of the maturation of young players, seems highly relevant. In addition, the present SLS aims to specifically target the feedback corrective sensorimotor control, whereas other tests also encompass feedforward preplanned motor actions (52). Therefore, other tests may be included in a test battery to encompass the total spectrum of relevant coordinative skills.

We acknowledge that the need of a force plate to measure COPspeed is a drawback for field assessments. Despite this,

there exist portable force plates and also more readily available ones, which might fulfill the needs of a strength and conditioning coach (22,29).

In conclusion, in male elite youth soccer players of 9–18 years, COPspeed—assessed with 2 repetitions of SLS for both legs—was age-dependent with lower values and lower variance for older players. Age-matched z-scores were determined, and within-session and between-session reliability seemed to be acceptable to distinguish players with deviant levels of SLS performance irrespective of age. Finally, for monitoring personal development of sensorimotor control, the CD of COPspeed determined here can be used. This in combination with baseline values allows for better detection of impairments in sensorimotor control compared with a population-based reference interval.

### PRACTICAL APPLICATIONS

Practitioners and coaches may use the current age-matched z-scores of COPspeed single-leg balance for performance monitoring in relation to peers, as well as to signify abnormal total body sensorimotor control (z-score above 1.96). Furthermore, the age-matched z-scores can be applied to all age groups, which enables monitoring of personal development over the years. The presented CD allows for a better detection of abnormal change in performance than a population-based reference. For instance, the CD is essential in concussion management, but can also be used as a screening method to detect underlying physical impairments. Finally, with respect to other tests or populations, the presented methods could serve as a guidance on how to use and interpret test results.

### ACKNOWLEDGMENTS

The results of this study do not constitute endorsement of the product by the authors or the NSCA. The authors thank Dr. Max Feltham and Dr. Kasper Kampinga for their useful comments while preparing this manuscript.

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